A Brief Characterization of Reciprocating Engines in Combined Heat and Power Applications

from

Technology Characterization: Reciprocating Engines
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Introduction and Summary

Combined heat and power (CHP) refers to the strategic placement of electric power generating units at or near customer facilities to supply on-site energy needs. CHP enhances the advantages of distributed generation by the simultaneous production of useful thermal and power output, thereby increasing the overall efficiency, and offers energy and environmental benefits over electric-only and thermal-only systems.

Reciprocating internal combustion engines are a widespread and well-known technology. A variety of stationary engine products are available for a range of power generation market applications and duty cycles including standby and emergency power, peaking service, intermediate and baseload power, and CHP. Reciprocating engines are available for power generation applications in sizes ranging from a few kilowatts to over 5 MW. They start quickly, follow load well, have good part-load efficiencies, and generally have high reliabilities. Spark ignition (SI) engines for power generation use natural gas as the preferred fuel, but can be set up to run on propane, gasoline, or landfill gas.

Current generation natural gas engines offer low first cost, fast start-up, proven reliability when properly maintained, excellent load-following characteristics, and significant heat recovery potential. Waste heat recovered from the hot engine exhaust and from the engine cooling systems produces either hot water or lower pressure steam for CHP applications. Overall CHP system efficiencies (electricity and useful thermal energy) of 70 to 80 percent are routinely achieved with natural gas engine systems. While the use of reciprocating engines is expected to grow in various distributed generation applications, the most prevalent on-site generation application for natural gas SI engines has traditionally been CHP, and this trend is likely to continue. The economics of natural gas engines in on-site generation applications is enhanced by effective use of the thermal energy contained in the exhaust gas and cooling systems, which generally represents 60 to 70 percent of the inlet fuel energy.

There are four sources of usable waste heat from a reciprocating engine: exhaust gas, engine jacket cooling water, lube oil cooling water, and turbocharger cooling. Recovered heat is generally in the form of hot water or low pressure steam (<30 psig). The high temperature exhaust can generate medium pressure steam (up to about 150 psig), but the hot exhaust gas contains only about one half of the available thermal energy from a reciprocating engine. Some industrial CHP applications use the engine exhaust gas directly for process drying. Generally, the hot water and low pressure steam produced by reciprocating engine CHP systems is appropriate for low temperature process needs, space heating, portable water heating, and to drive absorption chillers providing cold water, air conditioning, or refrigeration. There were an estimated 1,055 engine-based CHP systems operating in the United States in 2000, representing over 800 MW of electric capacity.[2] SI engines fueled by natural gas or other gaseous fuels represent 84% of the installed reciprocating engine CHP capacity (60% of landfill gas CHP projects use engines, based on the current LMOP database).

Performance Characteristics

Table 1 (modified Table 2 from *Technology Characterization: Reciprocating Engines*) summarizes performance characteristics for typical commercially available natural gas SI engine CHP systems for 800 kW and 3,000 kW sizes (typical sizes for landfill gas use). Heat rates and efficiencies shown were taken from manufacturers' specifications and industry publications. Available thermal energy was calculated from published engine data on engine exhaust temperatures and engine jacket and lube system coolant flows. CHP thermal recovery estimates are based on producing hot water. The data in the table show that electrical efficiency increases as engine size becomes larger. As electrical efficiency increases, the absolute quantity of thermal energy available to produce useful thermal energy decreases per unit of power output, and the ratio of power to heat for the CHP system generally increases. A changing ratio of power to heat impacts project economics and may affect the decisions that customers make in terms of CHP acceptance, sizing, and the desirability of selling power.

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[2] PA Consulting *Independent Power Database*, Energy Nexus Group

Footnote numbering is maintained from the original document.

Table 1. Gas Engine CHP - Typical Performance Parameters*

Baseload Electric Capacity	800 kW	3,000 kW
Cost & Performance Characteristics[9]		
Total Installed Cost (2001 $/kW)[10]	$1,000	$920
Electric Heat Rate (Btu/kWh), HHV[11]	10,246	9,492
Electrical Efficiency (%), HHV	33.3%	36.0%
Engine Speed (rpm)	1,200	900
Fuel Input (MMBtu/hr)	8.20	28.48
Required Fuel Gas Pressure (psig)	<3	43
CHP Characteristics		
Exhaust Flow (1000 lb/hr)	10.9	48.4
Exhaust Temperature (Fahrenheit)	869	688
Heat Recovered from Exhaust (MMBtu/hr)	2.12	5.54
Heat Recovered from Cooling Jacket (MMBtu/hr)	1.09	4.37
Heat Recovered from Lube System (MMBtu/hr)	0.29	1.22
Total Heat Recovered (MMBtu/hr)	3.50	11.12
Total Heat Recovered (kW)	1,025	3,259
Form of Recovered Heat	Hot H_2O	Hot H_2O
Total Efficiency (%)[12]	76%	75%
Power/Heat Ratio[13]	0.78	0.92
Net Heat Rate (Btus/kWh)[14]	4,774	4,857
Effective Electrical Efficiency[15]	0.71	0.70

* For typical systems commercially available in 2001
Source: Energy Nexus Group

[9] Characteristics for "typical" commercially available natural gas engine gensets. Data based on: Caterpillar G3516 LE - 800 kW; Caterpillar G3616 LE - 3 MW. Energy use and exhaust flows normalized to nominal system sizes.
[10] Installed costs based on CHP system producing hot water from exhaust heat recovery (250 deg F exhaust from heat recovery heat exchanger), and jacket and lube system cooling.
[11] All engine manufacturers quote heat rates in terms of the lower heating value (LHV) of the fuel. However, the purchase price of fuels on an energy basis is typically measured on a higher heating value (HHV) basis. The average heat content of natural gas is 1,030 Btu/kWh on an HHV basis and 930 Btu/kWh on an LHV basis - or about a 10% difference.
[12] Total CHP Efficiency = (net electric generated + net thermal energy recovered)/total engine fuel input
[13] Power/Heat Ratio = (CHP electric power output (Btus))/useful thermal output (Btus)
[14] Net Heat Rate = (Total fuel input to the CHP system - the fuel that would normally be used to generate the same amount of thermal output as the CHP system thermal output assuming an efficiency of 80%)/CHP electric output (kW)
[15] Effective Electrical Efficiency = (CHP electric power output)/(Total fuel into CHP system - total heat recovered/0.8); Equivalent to 3,412 Btu/kWh/Net Heat Rate.

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Table 2 (modified Table 3) provides cost estimates for combined heat and power applications. The CHP system is assumed to produce hot water. The heat recovery equipment consists of the exhaust silencer that extracts heat from the exhaust system, process heat exchanger for extracting heat from the engine jacket coolant, circulation pump, control system, and piping. These cost estimates include interconnection and paralleling. The engines have low emission, lean-burn technology. The interconnect/electrical costs reflect the costs of paralleling a synchronous generator. Labor/materials represent the labor cost for the civil, mechanical, and electrical work and materials such as ductwork, piping, and wiring. Project and construction management also include general contractor markup and bonding and performance guarantees. Contingency is assumed to be 3 percent of the total equipment costs.

Table 2. Estimated Capital Cost for Typical Gas Engine Generators in Grid Interconnected, Combined Heat and Power Application ($/kW)

Nominal Capacity		**800 kW**	**3,000 kW**
Costs ($/kW)			
Equipment	Gen Set Package	$269	$400
	Heat Recovery	$89	$65
	Interconnect/Electrical	$40	$22
Total Equipment		$398	$487
Labor/Materials		$379	$216
Total Process Capital		$777	$703
Project and Construction Management		$121	$95
Engineering and Fees		$45	$41
Project Contingency		$28	$25
Project Financing (interest during construction)		$31	$55
Total Plant Cost ($/kW)		$1,002	$919

Source: Energy Nexus Group

Table 3 (modified Table 5) presents maintenance costs based on engine manufacturer estimates for service contracts consisting of routine inspections and scheduled overhauls of the engine generator set. Costs are based on 8,000 annual operating hours expressed in terms of annual electricity generation.

Table 3. Typical Natural Gas Engine Maintenance Costs*

Electricity Capacity	**800 kW**	**3,000 kW**
Maintenance Costs[17]		
Variable (service contract) ($/kWh)	0.009	0.009
Variable (consumables) ($/kWh)	0.00015	0.00015
Fixed ($/kW-yr)	4	1.5
Fixed ($/kWh @ 8000 hrs/yr)	0.0005	0.00019
Total O&M Costs ($/kWh)	0.0097	0.0093

* Typical maintenance costs for gas engine gensets 2001

[17] Maintenance costs are based on 8,000 operating hours expressed in terms of annual electricity generation. Fixed costs are based on an interpolation of manufacturers' estimates. The variable component of the O&M cost represents the inspections and overhaul procedures that are normally conducted by the prime mover original equipment manufacturer through a service agreement, usually based on run hours.

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